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Luminosity limits on white dwarfs in a Galactic shroud

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ABSTRACT

We place observational constraints on a recently proposed Galactic population, dubbed the *shroud* (Gyuk & Gates 1999, Gates & Gyuk 2001). The shroud would be a very thick Galactic disk of low luminosity objects, most likely old white dwarfs, proposed to explain the optical depth seen in microlensing surveys towards the Magellanic clouds. The shroud is a simple alternative to the lenses being distributed in a classical, near-spherical dark halo; the advantage of the shroud is that it would compose only a fraction of a dark halo's total mass.

In this paper, we argue that stars of the Galactic shroud would be detectable in the recent proper motion survey of Oppenheimer et al. (2001) if their absolute luminosities were brighter than $M_{R_{59F}} = 19.4$ or approximately $M_V = 18.6$. We adopt a range of simple models of the shroud's kinematics and morphology, and the colours and luminosities of its white dwarfs; via Monte-Carlo simulations, we predict the numbers expected in the Oppenheimer et al. survey, which would be clearly separated from the numbers produced by white dwarfs of the disk, thick disk and halo.

The number of white dwarf detections in the proper motion survey (98) is found to be well explained by the disk, thick disk and halo. With *the most conservative* kinematic and density parameters for the shroud, and an absolute luminosity of the white dwarfs of $M_{R_{59F}} = 17.6$, we find that the proper motion survey would detect over 100 WDs, just from the shroud. For a $M_{R_{59F}} = 19.4$ shroud, the survey would find 5 ± 2 peculiar objects, whereas only two white dwarfs with such characteristics are found in the original data. $M_{R_{59F}} = 19.4$ corresponds to $M_V = 18.6$ for WDs with $(V - I) = -1.030$.

Key words: Galaxy: dark matter — Galaxy: structure — stars: white dwarfs

1 INTRODUCTION

The microlensing surveys carried out in recent years (e.g. EROS, MACHO and OGLE) have reported on lensing population of dark objects seen towards the Magellanic clouds. The favoured mass for these objects is approximately half a solar mass, suggesting they are white dwarfs, since main sequence M stars of this mass are bright enough to be detected directly in surveys. To date, no directly detected counterpart for the dark population has been found. One scenario is a population of ancient white dwarfs (WDs) which would comprise a significant fraction of the Galactic dark halo (up to 20 per cent of its mass). This suggestion has later become disfavoured because even quite dim WDs would be directly detectable in the most recent proper motion surveys even if they comprised 'only' 2 per cent of the total mass of the dark halo (Reylé, Robin & Crézé 2001; Flynn, Holopainen & Holmberg 2003).

To explain the MACHO microlensing results (Alcock et al. 2000), and at the same time to avoid some of the problems with a massive dark halo population, Gates and Gyuk (hereafter, G&G) (1999, 2001) proposed a new population in the Milky Way, dubbed the Galactic 'shroud'. It would be a WD population in the form of a very thick disk with a scale height of 2.0 – 3.0 kpc. It would produce the same microlensing optical depth as a dark halo WD population without having to be enormously massive.

We study here the implications of the shroud using the same techniques that we used in a previous study (Flynn et al. 2003; hereafter, Paper I). In Paper I, we constrained the luminosity and the number density of a dark halo WD population with the same simulation that we use for the current study. In the previous study, we used two proper motion surveys independently for constraining the halo population. After testing the simulation for Paper I, we are now confi-

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dent to use only the more recent one of those surveys (Oppenheimer et al. 2001) for constraining the new population.

Oppenheimer et al. proper motion survey was originally designed to find dark halo WDs. However, the follow up studies that have investigated the possibility of dark halo WDs in this survey have found that the survey is also very sensitive to the conventional thick disk WDs (e.g., Paper I; Reid, Sahu & Hawley 2001; Reylé et al. 2001). Because the shroud has a similar velocity structure to the thick disk, the survey is also very sensitive to the shroud. Thus, the Oppenheimer et al. survey is optimal for our purposes.

In section 2, we briefly introduce how to find nearby WDs and separate them by stellar population. In section 3, we go through the parameters of the model in detail, and in section 4, we describe the Oppenheimer et al. proper motion survey and its findings. We illustrate the effect of proper motion to the predicted number counts in section 5 and present our results in section 6. Finally, we conclude in section 7.

2 WHITE DWARF POPULATION SEPARATING TECHNIQUES

In our study, we are dealing with old (age > 10 Gyr) dim WDs, which have cooled to surface temperatures of 3000 − 4000 K and luminosities of less than 1×10^{-4} $L_\odot$. At present, detecting such white dwarfs in ground based surveys is limited to the solar neighbourhood (< 100 pc). This hampers the detection of any density gradient with distance which could be used to assign white dwarfs to various Galactic stellar populations. Consequently, the population to which a local white dwarf belongs can only be determined from its kinematics, since the different populations have different rotation velocities and velocity dispersions. The exception is for younger white dwarfs of the disk; being younger these WDs are brighter, and their luminosities assist in assigning a population type (for a detailed review on identifying WDs, see Hansen & Liebert 2003).

Field white dwarfs can be extracted from catalogs via their proper motions, magnitudes and colours, or the combination of apparent magnitude and proper motion termed the 'reduced proper motion', H_X. It is defined as

$$H_X = X + 5log(\mu) + 5 = M_X + 5log(V_{\rm tan}) - 3.38, \qquad (1)$$

where X is the apparent magnitude, μ is the proper motion in arcseconds per year, M_X is the absolute magnitude and $V_{\rm tan}$ is the tangential space motion in km s^{-1}.

Extremely high values of the reduced proper motion (for example, $H_V \sim 24$) indicate stars which are intrinsically dim and fast moving; both criteria of interest when searching for dim stars which would make up either a dark halo or dark shroud around the Galaxy.

At present, the state-of-the-art in finding intrinsically dim WDs is via proper motion surveys, selection of the high reduced proper motion objects, followed by detailed spectroscopy of all the candidates (for a list of the latest studies, see Hansen & Liebert 2003). The best survey to date is that of Oppenheimer et al. (2001), which has been augmented later by Salim et al. (2003). The two groups have identified some 98 dim white dwarfs in a 4000 square degree survey at the SGP, reaching to $V \sim 20$.

3 THE MODEL PARAMETERS OF THE SHROUD

3.1 A new very thick disk

The shroud is a *very thick* Galactic disk and has a scale height two to three times higher than the conventional thick disk. The main motive for proposing the existence of the shroud is a need to explain a microlensing optical depth $\tau \sim 10^{-7}$ towards the LMC (Alcock et al. 2000). This value can be explained with a massive dark halo of WDs. However, the progenitor stars of this population would require a highly peaked IMF and should pollute the Galaxy with metals (e.g., Brook et al. 2003).

Explaining the optical depth with an extended thick disk instead of a dark halo offers an alternative solution. This is because the required total mass of the population can be brought down from the dark halo's $\sim 10^{12}$ $M_\odot$ to the shroud's $\sim 6 \times 10^{10}$ $M_\odot$. This alleviates the pollution problem, although certainly not entirely.

G&G describe the shroud in detail in Gyuk & Gates 1999 (GG99) and Gates & Gyuk 2001 (GG01). The first paper constrains the model parameters, and in the second paper, G&G propose that the shroud consists of ancient white dwarfs. We examine the white dwarf scenario, which is based on the general models presented in GG99 (this paper is also the source for more detailed description of the models for the interested reader). We adopt the parameters and constraints given in GG99, and then, we explore how these constraints and the capabilities of the proper motion survey together limit the number of detectable shroud WDs.

3.2 Density structure

In GG99, G&G give two radial density models for their extended thick disk:

$$\Sigma(r) = \Sigma_0 \exp[(r_0 - r)/r_d] \qquad (2)$$

and

$$\Sigma(r) = \Sigma_0 \frac{r_0 + a}{r + a}, \qquad (3)$$

where the first is a model similar to the standard thick disk and the second resembles a flattened halo. Here, Σ is the surface density, Σ_0 is the surface density at the Sun's Galactocentric radius, r is the Galactocentric radius, a is a core radius, r_d is the scale length of the extended thick disk and r_0 is the Galactocentric radius of the Sun. Thus, the models are parametrized by surface density, Σ_0, which is typically in the range

$$60\,\mathrm{M_\odot pc^{-2}} \le \Sigma_0 \le 115\,\mathrm{M_\odot pc^{-2}}. \qquad (4)$$

G&G adopt two density distributions for the extended thick disk as a combination of the radial direction (exponential or $(r+a)^{-1}$) and the vertical direction (sech^2) distributions:

$$\rho(r,z) = \frac{\Sigma_0}{2h_z} \exp[(r_0 - r)/r_d] \mathrm{sech}^2(z/h_z) \qquad (5)$$

and

$$\rho(r,z) = \frac{\Sigma_0}{2h_z} \frac{r_0 + a}{r + a} \mathrm{sech}^2(z/h_z) \qquad (6)$$

We are interested only in constraining the local density at the Sun $\rho_0 = \rho(r_0, 0)$, i.e. $\rho_0 = \frac{\Sigma_0}{2h_z}$. We consider scale heights in the range

$$2.0\,\mathrm{kpc} \le h_z \le 3.0\,\mathrm{kpc}, \tag{7}$$

following the constraints from GG99.

The modeled shrouds are parametrized by surface density, Σ_0 and scale height, h_z. These two parameters form a parameter space which is constrained by observational values of i) optical depth, $\tau \ge 10^{-7}$; ii) rotation velocity of the shroud, $v_c \le 180$ km s^{-1}and iii) total vertical column density of the disk within 1.0 kpc, $\Sigma_{tot,1.0} \le 90$ M$_\odot$ pc^{-2} (for references, see GG99). By combining the ranges of Σ_0 and h_z, the local mass density range becomes

$$0.010\,\mathrm{M_\odot pc^{-3}} \le \rho_0 \le 0.029\,\mathrm{M_\odot pc^{-3}}. \tag{8}$$

We adopt a WD mass of $m_{WD} = 0.6$ M$_\odot$, leading finally to the space density of nearby WDs, ρ_n, in the range

$$0.0167\,\mathrm{stars\,pc^{-3}} \le \rho_n \le 0.0483\,\mathrm{stars\,pc^{-3}}. \tag{9}$$

3.3 Velocity structure

G&G do not restrict the rotation velocity of their model too much. They allow a range $v_c = 130 - 180$ km s^{-1}. We use these values as our lower and upper limit. We use a solar rotation velocity of $v_\odot = 220$ km s^{-1}, and the v_c values convert to an asymmetric drift values in the range -90 km s^{-1}to -40 km s^{-1}. The vertical velocity dispersion is that of an isothermal disk:

$$\sigma_W = \sqrt{2\pi G \rho_0 h_z^2} = \sqrt{\pi G \Sigma_0 h_z} \tag{10}$$

Furthermore, G&G use a typical dependence in a disk population for the other dispersions (e.g. Binney & Tremaine 1987): $\sigma_r \approx \sqrt{2}\sigma_W$ and $\sigma_\phi \approx \sigma_W$.

From the limits on Σ_0 and h_z above, we derive limits on the velocity dispersions of 57 km s^{-1}$\le \sigma_U \le 99$ km s^{-1}, 40 km s^{-1}$\le \sigma_V \le 70$ km s^{-1}and 40 km s^{-1}$\le \sigma_W \le 70$ km s^{-1}.

3.4 Luminosities of WDs

For cool, old, Hydrogen atmosphere white dwarfs (ages 10 to 14 Gyr), the expected luminosity range is roughly $16 \le M_V \le 18$ (Richer 2000, Hansen 2001). Models of WDs with ages of 13 – 14 Gyr which would have cooling curves down to $M_V = 19$ are not presently favoured, although they can be constructed. However, M_I values are not so well restricted because the cooling curves allow a large range of $M_V, (V-I)$ -dependencies.

G&G constrain the luminosity of the shroud in the I-band, based on counts of faint sources in the Hubble Deep Field, whereas we use the R_{59F}-band of the Oppenheimer et al. survey. We do not constrain the shroud based on the I-range of G&G but on the cooling curves and evolution models of WDs.

Realistically, any dim ancient white dwarf population must have a present day luminosity function (LF) which is a reflection of the initial mass function in the WD progenitors. Simulating the star formation and evolution process via isochrones and cooling curves is no simple matter. We do not attempt to test here plausible LFs other than a simple delta function; i.e. all the WDs have the same luminosity. It turns out that this is the most conservative option one can adopt, as will be discussed in Section 5.2.

4 THE PROPER MOTION SURVEY

The Oppenheimer et al. (2001) (hereafter, OHDHS) proper motion survey is the most effective WD proper motion survey to date. The survey is complete to a detection limit of $R_{59F} < 19.7$, and the proper motion detection window is 0.33 arcsec yr^{-1} $\le \mu \le$ 3.0 arcsec yr^{-1}. The survey is most likely partially incomplete at the upper proper motion boundary. We make conservative assumptions in order to take this into account in Section 6.3. The survey covers 10 per cent of the sky, about 4000 square degrees at the SGP.

OHDHS found 38 high velocity white dwarfs among 98 WDs in total. The high velocity WDs were provisionally assigned to the dark halo by OHDHS; their data implied that some 2 per cent of the dark halo was in this (baryonic) form. In later studies (e.g., Paper I; Hansen & Liebert 2003; Reid, Sahu & Hawley 2001), most of the high velocity WDs have been assigned to the traditional thick disk and stellar halo. There are only 2 WDs in the survey that have reduced proper motion characteristics ($H_{R_{59F}} > 24$) which are not typical for any of the known populations.

In a follow up study, Salim et al. (2003) studied the 38 high velocity WDs in more detail using photometry and spectroscopy. They calibrated the photometric R_{59F}–band used by OHDHS to standard V. In Paper I, we used a similar colour transformation which was based on an empirical calibration of the R_{59F}–band to R using M dwarfs. Salim et al.'s transformation is quite close to the one we adopted in Paper I.

We use the R_{59F} calibration by Salim et al. at the end of this paper because it depends strongly on the $V-I$ colours of the WDs. Because $V-I$ colours for a WD population vary according to the WD type, age, mass and evolution model, the conversion from R_{59F} to standard magnitudes results to a wide range of M_V values for the population. Thus, we construct the shroud with absolute magnitude values in $M_{R_{59F}}$ and also simulate the OHDHS survey in this original band. We examine the transformation to M_V-magnitudes of $M_{R_{59F}}$ for a full range of plausible models in Section 6.4.

5 COUNTING THE SHROUD WHITE DWARFS

5.1 Proper motion window

The number of stars detectable within a proper motion window of a survey is:

$$N_\mu = \rho_n V \varepsilon_\mu, \tag{11}$$

where ρ_n is the number density of the population, V the survey volume and ε_μ the fraction of stars which are inside the proper motion window. For a test population of a given luminosity, $M_{R_{59F}}$, the volume is determined by the maximum detection distance for that population, r_{max}.

For the shroud, ε_μ is a function of the maximum detection distance (r_{max}), W-velocity dispersion (σ_W) and rotation velocity (v_c). Within the parameter ranges, ε_μ depends strongly on all three parameters.

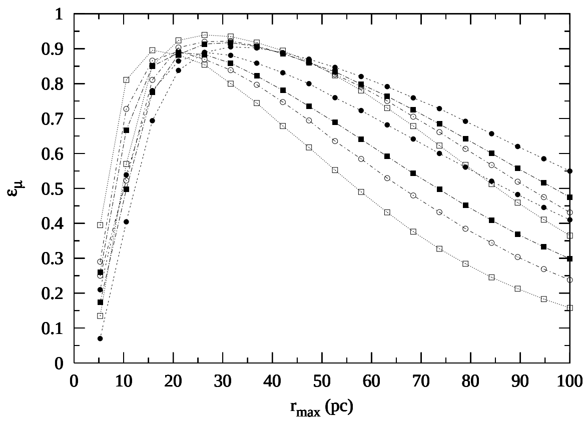

Figure 1. The μ–completeness of the survey for the shroud up to 100 pc. The differences between the number counts for the models are produced by differences in the parameters: r_{max}, σ_W and v_c. See Table 1 for model identification.

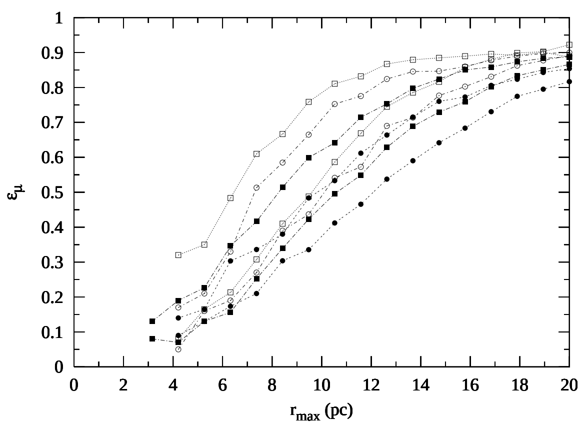

Figure 2. As for Figure 1, but 0 pc $< r_{max} <$ 20 pc. The μ–completeness of the survey is close to 90 per cent for the shroud with a detection distance of 20 pc. See Table 1 for model identification.

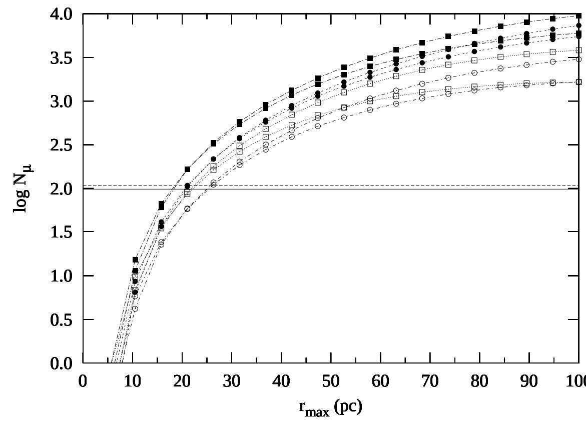

Figure 3. The number of shroud WDs (in logarithmic scale) which are inside the detection volume and have proper motion values 0.33 arcsec yr^{-1} $\leq \mu \leq$ 3.0 arcsec yr^{-1}. See Table 1 for model identification.

We can interpret ε_μ as the μ-completeness of a survey – it gives the probability that an object from a given population has a proper motion inside the proper motion window of the survey. In our case, ε_μ is the OHDHS survey μ-completeness for a given shroud. It is a convenient quantity because it is independent of the number density of the population.

The solid angle of the OHDHS survey is 10 per cent of the sky and results to a volume of:

$$V = \frac{\Omega}{3} r_{max}^3 = 0.419\, r_{max}^3. \qquad (12)$$

Now the equation for N_μ can be written:

$$N_\mu = 0.419\, r_{max}^3\, \rho_n(h_z, \Sigma_0)\, \varepsilon_\mu(r_{max}, v_c, \sigma_W) \qquad (13)$$

5.2 Reduced proper motion window

As mentioned in Section 2, a high H value indicates that the object is faint and has a large tangential space velocity. If we want to separate a peculiar population (like the shroud) from the known populations, one way is to search for unusually high H values. The OHDHS survey data shows that a suitable limit which will exclude the known populations effectively is $H_{R59F} > 24$. For example, for a $M_{R59F} = 16$ object, V_{tan} must be larger than 188 km s^{-1} to satisfy this limit.

The number of WDs which have extremely high reduced proper motion values can be expressed

$$N_{\mu H} = 0.419\, r_{max}^3\, \rho_n\, \varepsilon_{\mu H}, \qquad (14)$$

which is analogous to Equation 13. $\varepsilon_{\mu H}$ acts as ε_μ, only now it is the fraction of WDs which have 0.33 arcsec yr^{-1} $\leq \mu \leq$ 3.0 arcsec yr^{-1} *and* $H_{R59F} > 24$.

As mentioned in Section 3.4, we adopt a delta function for the LF for all our models. This procedure increases $N_{\mu H}$ while it minimizes N_μ. The fact that $N_{\mu H}$ is increased might be a problem because we use $N_{\mu H}$ to constrain shrouds which are extremely faint. To resolve the dependency between N_μ and $N_{\mu H}$ as a function of the shape of the LF, we ran simulations with 2 magnitude wide top-hat LFs and compared the results to models with delta function LFs; i.e. the top-hat LFs contained stars distributed equally up to two magnitudes brighter than those in the delta function LF. As expected, wide LFs always produce much higher N_μ values than a delta function LF, and we were able to constrain even the faintest shrouds only by N_μ. Thus, adopting a faint delta LF is the most conservative method for all our models, because it produces the smallest N_μ values for a given model.

6 RESULTS

6.1 Limiting the shroud by N_μ

We limit the number of detectable objects from the shroud in the OHDHS survey to $N_\mu^{max} = 108$. This is the 1-σ upper limit on the number of WDs which the OHDHS survey actually detected (98). The limits are shown as horizontal lines in Figures 3 and 4.

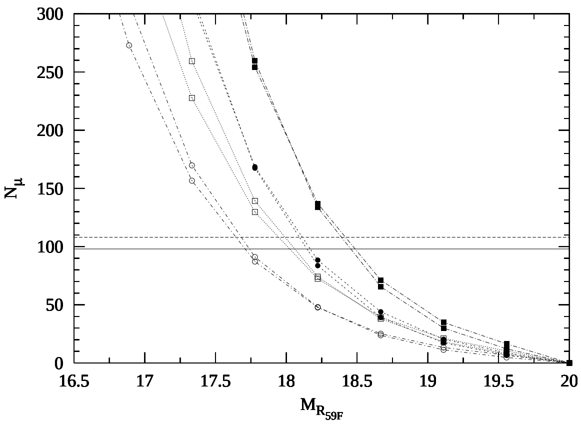

Figure 4. Another way to look at the results in Figure 3 with r_{max} converted to the absolute magnitude of the shroud with the limiting magnitude $R^{lim}_{59F} = 19.7$. See Table 1 for model identification.

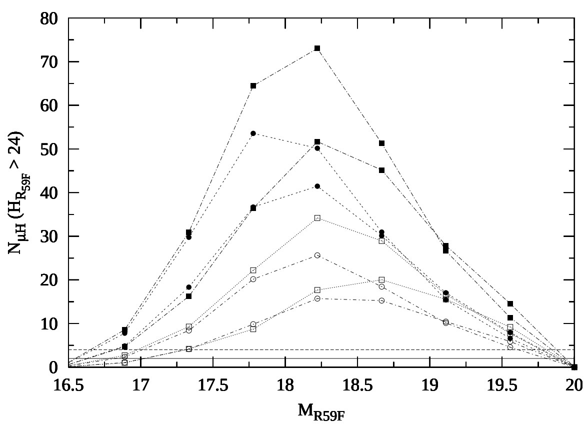

Figure 5. The number of shroud WDs which have a reduced proper motion value $H_{R_{59F}} > 24$. OHDHS detected 2 such WDs. See Table 1 for model identification.

In our highly conservative scenario, we assume that all the 98 WDs detected by the OHDHS survey are from the shroud and none are from the other Galactic populations. We do not attempt to subtract the disk component from these WDs, although it is highly probable that ~ 60 of the 98 WDs are from the thin disk based on their velocity components. Fortunately, $N^{max}_\mu = 108$ still sets some interesting limits on the luminosity of shroud WDs.

Figures 3 and 4 show the expected number of WDs in OHDHS for various shroud models and adopted WD luminosities. Changing the rotation velocity of the shroud affects the number counts considerably less than the changes in h_z and Σ_0: Each line style represents two models which are separated only by v_c-differences ($v_{c1} = 130$ km s^{-1}, $v_{c2} = 180$ km s^{-1}). Figure 4 shows clearly that the number counts are nearly equal in both cases.

Not surprisingly, the model which produces the lowest N_μ values has the lowest number density, $\rho_n = 0.0167$ stars pc^{-3}. The model can be seen in Figure 4 where it produces 108 WDs when its luminosity is $M_{R_{59F}} = 17.6$ or 17.7, depending on its rotation velocity. Thus, we consider models with $M_{R_{59F}} < 17.6$ to be so luminous that they can be ruled out directly by proper motion based number counts in the OHDHS survey.

Table 1. Symbols and parameters of the models presented in the figures.

Symbol	h_z kpc	Σ_0 M$_\odot$ pc^{-2}	σ_W km s^{-1}	v_c km s^{-1}
□	2.0	60.0	40.3	130.0, 180.0
○	3.0	60.0	49.3	130.0, 180.0
■	2.0	115.0	55.7	130.0, 180.0
•	3.0	115.0	68.3	130.0, 180.0

6.2 Limiting the shroud by $N_{\mu H}$

The fact that the OHDHS survey was able to find only 2 WDs with $H_{R_{59F}} > 24$ allows us to constrain the shroud to even fainter models than with the proper motion window.

We consider a model to be ruled out when it produces $N_{\mu H} > 4$ WDs. The original count of the OHDHS survey and the Poissonian 1-σ error limit are shown as horizontal lines in Figure 5.

Again, it turns out that the most conservative model at the low luminosity end is the one with the lowest number density. As in Section 6.1, the luminosity of the shroud is limited to nearly equal $M_{R_{59F}}$ values regardless of the rotation velocity of the limiting model. The model can be seen in Figure 5 where it produces 4 WDs when the WD luminosity is at either $M_{R_{59F}} = 17.0$ or 19.6. Thus, we consider models with $17.0 < M_{R_{59F}} < 19.6$ to be such that they can be ruled out directly by reduced proper motion based number counts in the OHDHS survey. This, together with the results presented in Section 6.1, rules out all the models which have $M_{R_{59F}} < 19.6$.

6.3 Proper motion incompleteness effect

In Sections 6.1 and 6.2, we have assumed that the OHDHS survey is 100 per cent complete to the upper limit of the proper motion window, $\mu_{max} = 3.0$ arcsec year^{-1}. OHDHS conduct a completeness test to resolve their brightness detection limit, but the completeness of their proper motion window is not fully resolved.

OHDHS estimate that stars with proper motions more than 3 arcsec year^{-1} have only 10 per cent chance to be found in their survey. Due to this uncertainty, we conducted additional simulations in which we assumed that the survey would be complete to only $\mu_{max} = 2.0$ arcsec year^{-1}. It turns out that this does not affect the results of Section 6.1 because most of the WDs have proper motions less than 2.0 arcsec year^{-1}. For Section 6.2 results, adopting the lower proper motion limit changes the most conservative brightness limit from $M_{R_{59F}} = 19.6$ to $M_{R_{59F}} = 19.2$ for the $v_c = 130$ km s^{-1} shroud. In the case of $v_c = 180$ km s^{-1}, the limit is changed by only 0.2 magnitudes, to $M_{R_{59F}} = 19.4$.

To further understand the effect of the proper motion window, we ran simulations with a changing completeness

level. We adopted a linear drop in the completeness level from 100 to 0 per cent for the range $1.5\,\mathrm{arcsec\,year}^{-1} < \mu < 3.1\,\mathrm{arcsec\,year}^{-1}$. This resulted in smaller effects than adopting a crude cut of $\mu_{max} = 2.0$ arcsec year^{-1} and changed the brightness limit at most from $M_{R_{59F}} = 19.6$ to $M_{R_{59F}} = 19.4$.

In the most conservative model, WDs with $H_{R_{59F}} > 24$ have a mean proper motion $\bar{\mu} \sim 1.3$ arcsec year^{-1}. Thus, adopting $\mu_{max} = 2.0$ arcsec year^{-1} instead of $\mu_{max} = 3.0$ arcsec year^{-1} for an upper limit does not have a large effect on the results presented in Sections 6.1 and 6.2. We consider the limit $M_{R_{59F}} = 19.4$ derived above to be very conservative within the given parameters.

6.4 Limiting the shroud luminosity in V-band

Finally, we want to transform the result presented in Section 6.3 to standard magnitudes. This is needed to link our models to general evolutionary models of WDs and evaluate how probable the shroud scenario is. We use the Salim et al. (2003) transformation between R_{59F} and V. This is based on photometry of 17 WDs which have been observed in the OHDHS survey. The transformation can be written

$$V - R_{59F} = 0.66(V - I) - 0.13, \tag{15}$$

and has a scatter in R_{59F} of $\sigma_{R_{59F}} = 0.09$. As mentioned in Section 3.4, this transformation is close to the transformation we used in Paper I (given here as a linear fit):

$$V - R_{59F} = 0.52(V - I) - 0.02. \tag{16}$$

The Salim et al. transformation is superior because it is based on actual WDs, rather than our earlier adopted transformation which was based on M dwarfs (Bessell 1986); no such WD data were available to us at the time.

We want to estimate a M_V-limit which would correspond to $M_{R_{59F}} = 19.4$ for the shroud WDs. From Equation 15, we see that this requires some $V - I$ range evaluation.

Salim et al. have measured or derived $V - I$ values for a subsample of the OHDHS WDs. The lowest value they can find is for LHS 1402, which has $V - I = -0.37$. We can rule out shrouds with $M_V < 19.0$ by adopting this value. It must be noted that LHS 1402 is not a typical WD in this sample (although it might be a fair representative of a shroud WD); adopting redder colours, from the other WDs, would result in even fainter limits.

We can also use the cooling curves of Richter et al. (2000) which for the faintest WDs predict $V - I$ values down to -1.030. This is for a 0.6 $M_\odot$ mass WD with an age of 15 Gyrs and a luminosity of $M_V = 18.1$. Adopting $V - I = -1.030$ rules out shrouds with $M_V < 18.6$.

G&G limit the shroud in I-band to $M_I \sim 16 - 17$. The above $V - I$ and M_V values can also be used to limit the shroud in I: The first estimate, $V - I = -0.37$, rules out shrouds with $M_I < 19.6$. The second value, $V - I = -1.030$, sets similar limits, shrouds with $M_I < 19.4$ are ruled out. The lowest limit in I can be found by using $V - I = 2.0$. This rules out shrouds with $M_V < 20.6$ and $M_I < 18.6$.

7 CONCLUSIONS

Strong limits have been placed on the luminosities of white dwarfs which could make up the putative ‘shroud’ of the Galaxy, proposed as a solution to the optical depth measurements seen in the microlensing surveys towards the Magellanic clouds. We use the Oppenheimer et al. (2001) proper motion survey of 4000 square degrees to $R_{59F} = 19.7$, containing 98 spectroscopically confirmed WDs. A range of shroud models are investigated, and the number of WDs with high reduced proper motions compared to the Oppenheimer et al. data. Most of the models produce significantly more WDs than are actually observed; in particular, models in which we probe the very highest reduced proper motion source (indicating very low luminosity and high space velocities, as expected for the shroud component) allow us to limit the luminosity of the WDs in the shroud to $M_{R_{59F}} = 19.4$ (the survey pass band), which corresponds to $M_V = 18.6$ or $M_I = 19.6$. If the Galaxy possesses a shroud of WDs which produces the microlensing signal, these WDs must be fainter than the above limits. Very few models of Hydrogen atmosphere WDs cool to such faint levels within the age of the Universe.

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